

# Origin of Thermal and Non-Thermal Hard X-ray Emission from the Galactic Center

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## Abstract

We analyse new results of *Chandra* and *Suzaku* which found a flux of hard X-ray emission from the compact region around Sgr A\* ( $r \sim 100$  pc). We suppose that this emission is generated by accretion processes onto the central supermassive blackhole when an unbounded part of captured stars obtains an additional momentum. As a result a flux of subrelativistic protons is generated near the Galactic center which heats the background plasma up to temperatures about 6 – 10 keV and produces by inverse bremsstrahlung a flux of non-thermal X-ray emission in the energy range above 10 keV.

**Key words:** Galaxy: center - X-rays: diffuse background - ISM: cosmic rays

## 1. Introduction

The X-ray emission of the order of  $10^{38}$  erg s<sup>-1</sup> from the Galactic ridge (GR) in the energy range above 1 keV was detected almost forty years ago (Bleach et al. 1972) but its

origin remains unknown till now. Two possibilities are debated either this emission is really diffuse (Ebisawa et al. 2005; Ebisawa et al. 2008) or it is due to an accumulative effect of faint X-ray sources (Revnivtsev et al. 2006). In the case of diffuse origin serious energetic problems arise if this emission is produced by non-thermal bremsstrahlung of high energy electrons, since the required power of sources of charged particles in the disk should exceed  $10^{42}$  erg s $^{-1}$ , i.e. higher than the power of supernovae in the Galaxy (Skibo et al. 1996; Valinia et al. 2000; Dogiel et al. 2002a). However, this energy problem can be solved if the particles are in-situ accelerated from background plasma (Dogiel et al. 2002b; Dogiel et al. 2007).

An alternative explanation of emission from GR was developed by Revnivtsev et al. (2006) who presented recently essential arguments in favor of the idea that the Galactic ridge emission was due to cumulative emission of faint discrete X-ray sources. Though this interpretation is not completely proved at present, it appears to be plausible. Revnivtsev et al. (2006) showed that the 3 – 20 keV map of GRXE as well as the 6.7 keV iron line distribution in the disk closely follow the near-infrared ( $3.5 \mu$ ) brightness distribution which traces the galactic stellar mass distribution. This proportionality is the same in the disk and in the bulge. From recent Suzaku observations it was concluded that the soft X-ray disk emission in the range 0.4 to 1 keV from the latitudes  $< 2^\circ$  originated also from faint dM stars (Masui et al. 2009).

Very decisive analysis about the origin of the Galactic ridge emission was provided recently by Revnivtsev et al. (2009). From the Chandra data they showed that most ( $\sim 88\%$ ) of the ridge emission is clearly explained by dim and numerous point sources. Therefore, at least in the ridge emission, accreting white dwarfs and active coronal binaries are considered to be main emitters.

The situation in the Galactic center (hereafter GC) may be quite different. The GC region has been observed by X-ray experiments flown for almost 30 years (see Watson et al. 1981; Kawai et al. 1988). Latter *Ginga* made a remarkable measurements of the spectra in this region (Koyama et al. 1989; Yamauchi et al. 1990). Though as in the case of GRXE, observations show there a significant contribution of discrete sources with luminosity  $L_{2-10 \text{ keV}} > 10^{31}$  erg s $^{-1}$  which contribute from 20% to 40% of the total flux (Muno et al. 2004; Revnivtsev et al. 2007), the origin of the rest of the flux is still unknown and essential distinctions were found between flux characteristics from GRXE and GC. First of all, the GC emission is seen as a completely separated spherical region around Sgr-A\* whose radius is about 100 – 200 pc (Muno et al. 2004; Koyama et al. 2007). The plasma temperature there is higher than in other part of the Galactic disk. Secondly, the ratios of 6.9 to 6.7 keV lines (which traces the plasma temperature) and 6.4 to 6.7 keV lines are higher in GC than in GR, while in GR this ratio is almost constant along the plane (Yamauchi et al. 2009). Thirdly, unlike the above-mentioned correlation of Revnivtsev et al. (2006) the X-ray source distribution derived from *Chandra* deep exposure of the  $< 0.3^\circ$ -radius central region does not show any correlation with the distribution of 6.7 keV line (Koyama et al. 2007). Therefore, they concluded that the integrated flux of

point sources contributed a rather small fraction of the total flux of GC X-rays and the major of emission from there is diffuse.

This leaves an open possibility that the nuclear region of the Galaxy (within  $\sim 10' - 1^\circ$  around Sgr A\*) may be somewhat different from the rest of the Galaxy, and, therefore, processes of radiation there have an origin which differs from other parts of the Galactic disk.

This region is known, indeed, to be peculiar in many respects:

- The plasma temperature in the GC region is higher ( $\sim 10$  keV) than in other parts of the Galactic disk. Such a high plasma temperature is surprising, since the gravitational potential in the GC region is no greater than several hundred eV which is too small to bind the gas. The plasma could not be gravitational confined and a very high amount of energy is required to maintain the plasma outflow. This energy supply cannot be produced by SN explosions and other more powerful sources of energy are required to support the energy balance there (Sunyaev et al. 1993; Koyama et al. 1996; Muno et al. 2004) ;
- GC region is a source of annihilation emission whose origin is still enigmatic. It may be explained either by emission of point sources like nova and supernova (see e.g. Dermer & Murphy 2001) or low mass X-ray binaries (Weidenspointner et al. 2008), or by dark matter annihilation (Sizun et al. 2006);
- Intensive emission in X-ray iron lines is observed from the Galactic center, which is often explained that the gas there was exposed in the past by sources of intensive X-ray emission e.g. from a supernova or from the Galactic nucleus (Sunyaev et al. 1993; Koyama et al. 1996);
- The temperature of molecular hydrogen ( $H_2$ ) in GC is unusually high,  $T = 100 - 200$  K. With the exception of Sgr B2 no embedded source are observed inside clouds. Therefore, a global heating mechanism is needed to explain the high gas temperature, e.g. by cosmic rays (see e.g. Yusef-Zadeh et al. (2007));
- The flux of VHE gamma-rays of unknown origin was discovered by HESS in the direction of GC, which is supposed due to processes nearby the central black hole (Aharonian & Neronov 2005).

As one can see, each of these observational phenomena can be explained separately by completely different physical processes which are not concerned with each others.

We assume, however, that these phenomena have common origin, namely, they are consequences of star accretion onto the central supermassive black hole. As our estimations showed the energy produced by accretion in the form of relativistic and subrelativistic particles is so high that it is inaccessible for any other sources of energy in the Galaxy. Another important

characteristic of this process is that the energy erupted in GC is conserved there for rather long time because of relatively slow dissipation time of primary and secondary charged particles generated by accretion processes. We developed this model in series of papers (Cheng et al. 2006; Cheng et al. 2007; Dogiel et al. 2008; Dogiel et al. 2009a), in which we interpreted the origin of annihilation emission and estimated the flux of gamma-ray de-excitation lines from GC. This publication is a continuation of these investigations.

Below we present a model of thermal and non-thermal hard X-ray emission from the GC which is supposed to be due to specific processes of accretion on the central black hole. We restrict our analysis by integral characteristics of this emission, its spatial variations are beyond the scope of this paper. We suppose to present such an analysis in our following publication. The goal of this paper is to demonstrate a principle possibility of of X-ray production in the GC (thermal and non-thermal) by subrelativistic protons at the level observed by Suzaku.

## 2. Proton Injection and Plasma Heating. The Origin of Thermal X-ray Emission from GC

Processes of injection of subrelativistic protons by star accretion were described in details in Dogiel et al. (2009a). Here we remind only the main parameters of the process.

Every star capture by supermassive black holes releases a huge energy which is several order of magnitude higher than produced by a supernova explosion. The average frequency capture of one solar mass stars by supermassive black holes is about  $(1 - 10) \times 10^{-5} \text{year}^{-1}$  (see Donley et al. 2002 and Syer & Ulmer 1999). As it was shown by Ayal et al. (2000) once passing the pericenter, the star is tidally disrupted into a very long and dilute gas stream. Approximately 50 – 75% of the star matter was not accreted but instead became unbounded. This unbounded mass receives an additional angular momentum and escapes with velocities higher than the orbital speed that corresponds to the energy per baryon higher than

$$E_{esc} \sim \frac{2GM_{bh}m_p}{R_T} \sim 5 \times 10^7 M_6^{2/3} m_*^{1/3} r_*^{-1} \text{ eV}. \quad (1)$$

For the mass of the black hole located in the center of our Galaxy is about  $(4.31 \pm 0.06) \times 10^6 M_\odot$  (see, Gillessen et al. 2009) it follows that the average energy of escaped particles may be more than 50 – 100 MeV nucleon<sup>-1</sup> when a one-solar mass stars is captured (see for details Dogiel et al. 2009a). Here  $R_T$  is the capture radius of a black hole given by

$$R_T \approx 1.4 \times 10^{13} M_6^{1/3} m_*^{-1/3} r_* \text{ cm}, \quad (2)$$

where  $m_* = M_*/M_\odot$ ,  $M_6 = M_{bh}/10^6 M_\odot$ ,  $r_* = R_*/R_\odot$ ,  $M_*$  and  $R_*$  are the star mass and radius,  $M_{bh}$  the mass of the black hole, and  $M_\odot$  and  $R_\odot$  are the solar mass and radius.

For these parameters after every capture event about  $10^{57}$  protons with energies  $\sim 100$  MeV escape into the surrounding medium whose temperature is  $\sim 6.5$  keV and the uniform target gas distribution was assumed (Koyama et al. 1996; Munro et al. 2004; Koyama et al.

2007). The rate of their energy losses is

$$\left(\frac{dE}{dt}\right)_i = -\frac{4\pi ne^4 \ln \Lambda_1}{mv_p}, \quad (3)$$

where  $v_p$  is the proton velocity, and  $\ln \Lambda_1$  is the Coulomb logarithm. Since the lifetime of subrelativistic protons

$$\tau_i = \int_E \frac{dE}{(dE/dt)_i}, \quad (4)$$

is about  $10^{14}$  s.

Since the proton lifetime is much longer than the characteristic time of star capture, the process of proton injection can be considered as quasi-stationary with the rate of proton injection in between from  $Q = 10^{45}$  to  $10^{46}$  protons  $s^{-1}$  (or the energy input  $\dot{W} \sim 10^{42}$  erg  $s^{-1}$ ).

The time-dependent spectrum of subrelativistic protons,  $N(\mathbf{r}, E, t)$  can be calculated from the equation

$$\frac{\partial N}{\partial t} - \nabla D \nabla N + \frac{\partial}{\partial E} (b(E)N) = Q(E, \mathbf{r}, t), \quad (5)$$

where  $D$  is the spatial diffusion coefficient of cosmic ray protons whose average value in the was taken to be  $D \simeq 10^{26}$  cm $^2$ s $^{-1}$  in order to reproduce the Suzaku data,  $dE/dt \equiv b(E)$  is the rate of proton energy losses, and  $Q(E, t)$  is the rate of proton production by accretion, which can be presented in the form

$$Q(E, \mathbf{r}, t) = \sum_{k=0} Q_k(E) \delta(t - t_k) \delta(\mathbf{r}), \quad (6)$$

where  $t_k$  is the injection time. The average time of star capture in the Galaxy was taken to be  $T \simeq 10^4$  years, then  $t_k = k \times T$ .

The energy distribution of erupted nuclei  $Q_k(E)$  is taken as a simple Gaussian distribution the energy distribution of these erupted nuclei is taken as a simple Gaussian distribution ( in order to avoid a simple delta function injection)

$$Q_k(E) = \frac{N}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(E - E_{esc})^2}{2\sigma^2} \right], \quad (7)$$

where we take the width  $\sigma = 0.03 E_{esc}$  with  $E_{esc} \simeq 100$  MeV, and  $N$  is total amount of particles ejected by one stellar capture.

In the nonrelativistic case when the rate of energy losses can be approximated as  $(dE/dt)_i \simeq a/\sqrt{E}$ , the solution (5) can be presented as

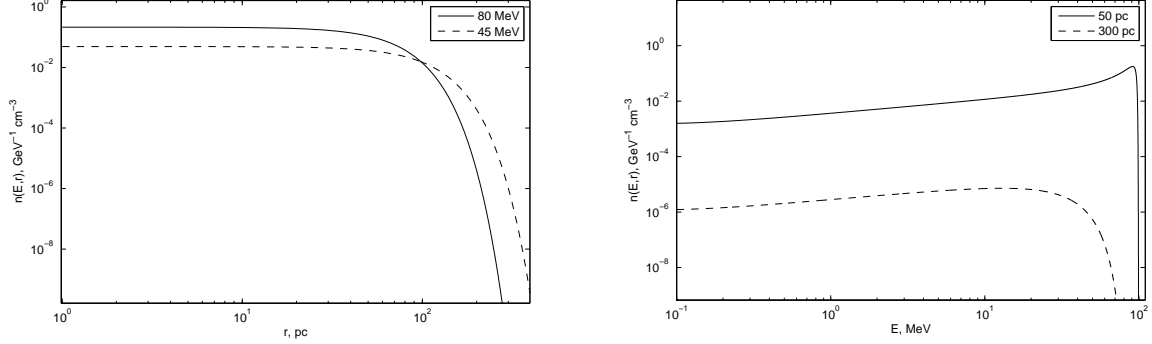
$$f(\mathbf{r}, E, t) = \sum_{k=0} \frac{N_k \sqrt{E}}{\sigma \sqrt{2\pi} Y_k^{1/3}} \frac{\exp \left[ -\frac{(E_{esc} - Y_k^{2/3})^2}{2\sigma^2} - \frac{\mathbf{r}^2}{4D(t-t_k)} \right]}{(4\pi D(t-t_k))^{3/2}}, \quad (8)$$

where

$$Y_k(t, E) = \left[ \frac{3a}{2}(t - t_k) + E^{3/2} \right]. \quad (9)$$

Below we use the following parameters of the model for calculations:  $Q = 2 \times 10^{45}$  protons  $s^{-1}$ ,  $E_{esc} = 100$  MeV. The plasma temperature in the GC derived from Suzaku data and it equals about 6.5 keV, and the average plasma density there is about  $0.2 \text{ cm}^{-3}$ .

As an example we show in figure 1 spatial and energy distributions of subrelativistic protons near the GC.



**Fig. 1.** (a) Spatial distribution of protons. (b) Energy spectrum of protons.

The energy releases in the Galactic center in the form of subrelativistic protons may effectively heat the plasma there. Last Suzaku observations of Koyama et al. (2007) found a clear evidence for a hot plasma in the GC with the diameter about 20 arcminutes (i.e.  $\sim 50 - 60$  pc). Total X-ray flux from this region in the range 2 to 10 keV is  $F_X \sim 2 \times 10^{36} \text{ erg s}^{-1}$ , total energy of plasma in this region is about  $3 \times 10^{52} \text{ erg}$ . The temperature derived from the continuous spectrum is about 15 keV but such a high value may be a result of contribution from a non-thermal component of X-ray emission. Indeed, from the 6.9/6.7 keV line ratio Koyama et al. (2007) concluded that the spectrum in 5 – 11.5 keV range was naturally explained by a 6.5 keV-temperature plasma in collisional ionization equilibrium.

The origin of the hot temperature plasma is unclear. Powerful sources of heating are required. However, there are no evident sources of energy in the Galactic central region. Sunyaev et al. (1993), Koyama et al. (1996) and Munro et al. (2004) concluded that the plasma in the  $1^\circ - 2^\circ$  radius central region can be heated up to the observed temperature  $T \sim 6 - 10$  keV if the energy release there is about  $\dot{W} \sim 10^{41} - 10^{42} \text{ erg s}^{-1}$  that cannot be provided by supernova explosions. Just this power can be supplied by subrelativistic protons which lose their energy mainly by ionization and thus heating of background plasma.

Undoubtedly, this very crude estimate of temperature is severely limited. In order to describe the temperature and gas distribution in GC when the energy is sporadically released due to star capture more sophisticated hydrodynamic and MHD calculations are required. In this respect we mention recent results of de Avillez & Breitschwerdt (2005) who simulated from 3D

numerical calculations the dynamical structure of interstellar medium in star formation region with respect to the volume and mass fractions of the different ISM "phases". Due to energy release from star explosions the medium is strongly nonuniform and turbulent. Compressed region of cold and dense filaments co-exist with a hot and low density plasma. This reminds the filamentary and non-uniform structure around GC.

### 3. 6.7 and 6.9 keV Iron Line Emission from GC

As follows from conclusions of the previous section subrelativistic protons heat effectively the background gas. We search below whether they generate also an excess of iron line emission in the X-ray flux from the GC as it was expected from in-situ accelerated non-relativistic electrons in the GRXE spectrum (Dogiel et al. 2002b; Masai et al. 2002). As follows from Dogiel et al. (1998) subrelativistic protons effectively produce shell vacancies that may be found in the line X-ray spectrum of the Galactic center.

Recent Suzaku observations with high energy resolution clearly resolved several iron lines in the spectrum of hot plasma into individual peaks of FeI  $K\alpha$  (6.4 keV), FeXXV  $K\alpha$  (6.7 keV), FeXXVI  $Ly\alpha$  (6.9 keV), FeXXV  $K\beta$  (7.8 keV), FeXXVI  $Ly\beta$  + FeXXV  $K\gamma$  (around 8.2 – 8.3 keV), and FeXXVI  $Ly\gamma$  (8.7 keV) (Koyama et al. 2007; Ebisawa et al. 2008). The FeI  $K\alpha$  emission is associated with molecular clouds and therefore it requires a special analysis which will be presented in other paper. The lines 6.7 keV and 6.9 keV, provide important information about the plasma parameters since their intensities are proportional to the number of iron ions.

The He-like  $K\alpha$  emission consists of emission lines of different transitions, and it might even contains emissions from Li-like ions in CCD energy resolutions. The photon-weighted centroid energy of the emission depends on the ionization process (e.g. collisional or photo ionization) and the emission process (e.g. thermal or non-thermal emission like charge exchange). The centroid energy derived from observation is consistent with that the GC plasma is in the collisional ionization equilibrium as it was claimed by Koyama et al. (2007). The ratio of 6.9/6.7 lines is proportional to abundances of FeXXV and FeXXVI iron ions which are functions of plasma temperature. From the best determined flux ratio of FeXXVI  $Ly\alpha$  and FeXXV  $K\alpha$  lines equaled 0.3 – 0.38 in GC region Koyama et al. (2007) concluded that the electron temperature is  $kT_e = 6.4 \pm 0.2$  keV. Yamauchi et al. (2009) showed that this ratio is almost constant in the Galactic disk but increases in almost two times in the direction of GC that indicates on higher temperatures in the Galactic center than in the disk.

In principle, a flux of subrelativistic protons may provide additional vacancies in iron ions that distorts the temperature estimation obtained from the line ratio. In order to estimate the effect from nonthermal protons one should accurately calculate 6.7 keV and 6.9 keV line intensities provided by thermal plasma and by nonthermal particles.

A correct analysis of the ratio 6.7/6.9 lines was provided by Prokhorov et al. (2009)

for the case of galaxy clusters who estimated a mimic temperature excess due to nonthermal particles. Below we present results of similar analysis for GC.

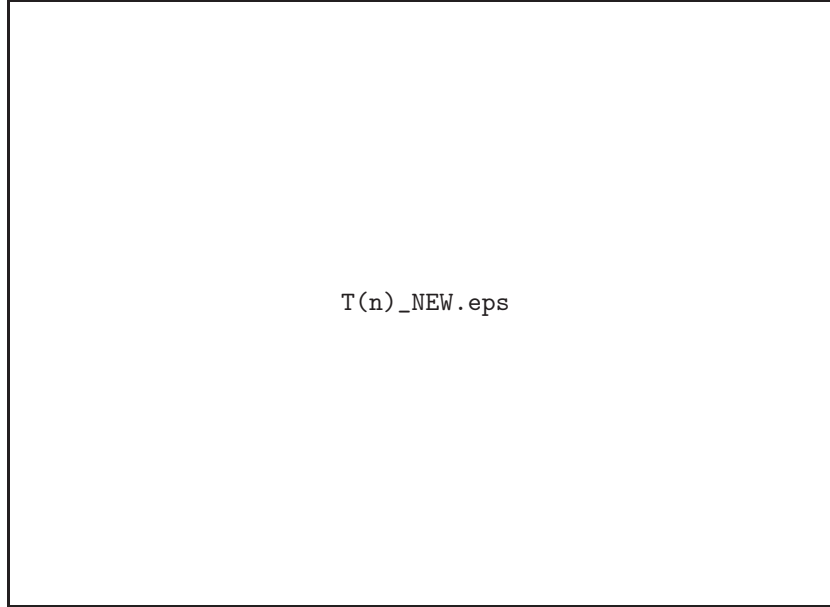
Taking into account both electron impact excitation and radiative recombination, the line flux ratio of FeXXVI Ly $\alpha$ /FeXXV K $\alpha$  is given by

$$R = \frac{\xi_{\text{FeXXVI}} Q_{\text{FeXXVI}}^{1-2} + \xi_{\text{FeXXVII}} \alpha_{\text{FeXXVI}}^{1-2}}{\xi_{\text{FeXXV}} Q_{\text{FeXXV}}^{1-2} + \xi_{\text{FeXXVI}} \alpha_{\text{FeXXV}}^{1-2}}, \quad (10)$$

where the coefficients  $Q_{\text{FeXXV}}^{1-2}$  and  $Q_{\text{FeXXVI}}^{1-2}$  describes processes of impact excitation by thermal electron and subrelativistic protons for FeXXV and FeXXVI respectively,  $\alpha_{\text{FeXXV}}^{1-2}$  and  $\alpha_{\text{FeXXVI}}^{1-2}$  are the rate coefficients for the contribution from radiative recombination of the spectral lines FeXXV (He-like triplet) and FeXXVI (H-like doublet) respectively.

The rate coefficients are obtained by averaging the product of cross section by particle velocity over the particle distribution function. The ionic fractions of  $\xi_{\text{FeXXV}}$ ,  $\xi_{\text{FeXXVI}}$  and  $\xi_{\text{FeXXVII}}$  are calculated for the case of thermal plasma with a nonthermal particle population. For corresponding references on cross sections of ionization, recombination and impact excitation etc, see Prokhorov et al. (2009).

In figure2 we presented the temperature of plasma derived from the observed 6.7/6.9 ratio which was fixed for the central region and equaled 0.33. The contribution from subrelativistic protons was calculated for the spectrum derived from equation (5). We calculated the real plasma temperature for the plasma density which changes in the range from 0.1 to 0.4 cm<sup>-3</sup>.



**Fig. 2.** Real temperature of plasma derived from the 6.7/6.9 ratio as a function of the plasma density, when ionization is provided also by subrelativistic protons.

We see that the contribution from subrelativistic protons is negligible ( $\leq 10\%$ ) and the calculated temperature is close to the one derived by Koyama et al. (2007) for the pure thermal

case. The reason is evident, the energy of lines are close to the plasma temperature, therefore, these lines are mainly excited by thermal particles.

We found that the value of the FeXXV  $K\alpha$  line intensity for the case with the nonthermal component differs from the pure thermal case in a factor less than 1% while intensity variations of the FeXXVI  $Ly\alpha$  line are more significant, they are at the level of several percents. Just variations of FeXXVI  $Ly\alpha$  line leads to a higher "effective temperature" ( $\sim 6.5$  keV) for the case of nonthermal particles contribution.

Our calculations show that "an X-ray signal" from subrelativistic protons can be found at energies higher than 10 keV where the influence of thermal emission is insignificant.

#### 4. Nonthermal Emission of Subrelativistic Protons from the GC

Suzaku data of Koyama et al. (2007) suggested that the continuum flux from the GC contained an additional hard component. Up to recently any direct confirmation of nonthermal emission at energies above 10 keV has been unavailable. Yuasa et al. (2008) performed analysis of Suzaku data and showed a prominent hard X-ray emission in the range from 14 to 40 keV whose spectrum is a power law with the spectral index ranging from 1.8 to 2.5. The total luminosity of the power-law component from the central region ( $|l| < 2^\circ$ ,  $|b| < 0.5^\circ$ ) is  $(4 \pm 0.4) \times 10^{36}$  erg s $^{-1}$ . The spatial distribution of hard X-rays correlates with the distribution of hot plasma.

This spectrum can be represented by an exponentially cutoff power-law model,

$$f(E) = K(E/1 \text{ keV})^{-\Gamma} \exp(-E/E_c), \quad (11)$$

with  $\Gamma$  and  $E_c$  varying from region to region over 1.2 - 2.2 and 19 – 50 keV, respectively.

Since the Hard X-ray Detector (HXD) onboard Suzaku is not an imaging detector, Yuasa et al. (2008) obtained the GC diffuse hard X-ray spectra by subtracting contamination fluxes from known bright X-ray point sources in its field of view ( $34' \times 34'$  FWHM). They considered contributions from those point sources with fluxes higher than  $1.5 \times 10^{-11}$  ergs cm $^{-2}$  s $^{-1}$  (or  $10^{-3}$  of a flux from Crab Nebula) in the 14 – 40 keV band, and subtracted them from observed spectra with assumptions such as their spectral shapes and fluxes are invariable during the observations. Resulting energy spectrum of the GC hard X-ray emission observed by the HXD after subtracting bright-point-source contaminations is shown in figure 3 by crosses.

The residual spectrum still contains contributions from dimmer point sources ( $< 1.5 \times 10^{-11}$  ergs cm $^{-2}$  s $^{-1}$  in the 14 – 40 keV band). Therefore before comparing the spectral shape and the luminosity of our model with observed ones, we estimated the remaining point source fluxes in the HXD spectra.

By integrating a luminosity function of X-ray point sources in the GC region <sup>1</sup> over

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<sup>1</sup> "field" curve shown in figure 13 of Muno et al. 2009 was used. In a small region around Sgr A\*, rather long exposure enabled high sensitivity and the luminosity function was measured in the dimmer flux range.

the luminosity range from  $2 \times 10^{32}$  ergs s $^{-1}$  to  $1 \times 10^{34}$  ergs s $^{-1}$  (in the 0.5 – 8 keV band; a distance of 8 kpc was assumed), we obtain a dim-point-source contaminating flux of  $\sim 1.1 \times 10^{-15}$  ergs cm $^{-2}$  s $^{-1}$  arcmin $^{-2}$ . In the estimation, we took into account the effective solid angle of the HXD/PIN of 1220 arcmin $^2$ , and assumed that a spectral photon index of the faint point sources is 1.5. The value is on the order of 10% of the HXD/PIN residual fluxes. If we further integrate the luminosity function, extrapolating the measured one with the same slope index down to  $2 \times 10^{31}$  ergs s $^{-1}$  and  $2 \times 10^{30}$  ergs s $^{-1}$ , the contaminating flux increase by 2.5 and 5.5 times ( $\sim 25\%$  and  $\sim 50\%$  of the HXD flux), respectively. Since a precise qualitative treatment of the contaminating point source flux is not a trivial procedure, we do not deal them further, and compare our model spectra directly with that of the HXD in the present analysis.

Interactions of subrelativistic protons with plasma result in production of bremsstrahlung photons (inverse bremsstrahlung radiation). Though the rate of these energy losses is negligible in comparison with the above-mentioned Coulomb energy losses, nevertheless, these losses generate emission in the energy range higher than the thermal emission of background plasma and hence can be observed. Subrelativistic protons generate bremsstrahlung photons with characteristic energies about  $E_X < (m/M)E_p$  where  $E_p$  is the kinetic energy of protons and  $m$  and  $M$  are the masses of an electron and a proton. For the proton energies  $E \leq 100$  MeV the bremsstrahlung radiation is in the range  $E_X < 55$  keV. The cross-section of inverse bremsstrahlung radiation is (Hayakawa 1969)

$$\frac{d\sigma_{\text{br}}}{dE_X} = \frac{8}{3} Z^2 \frac{e^2}{\hbar c} \left( \frac{e^2}{mc^2} \right)^2 \frac{mc^2}{E'} \frac{1}{E_X} \ln \frac{(\sqrt{E'} + \sqrt{E' - E_X})^2}{E_X}. \quad (12)$$

Here  $E' = (m/M)E_p$ . Then the total flux of inverse bremsstrahlung emission from the GC can be calculated from

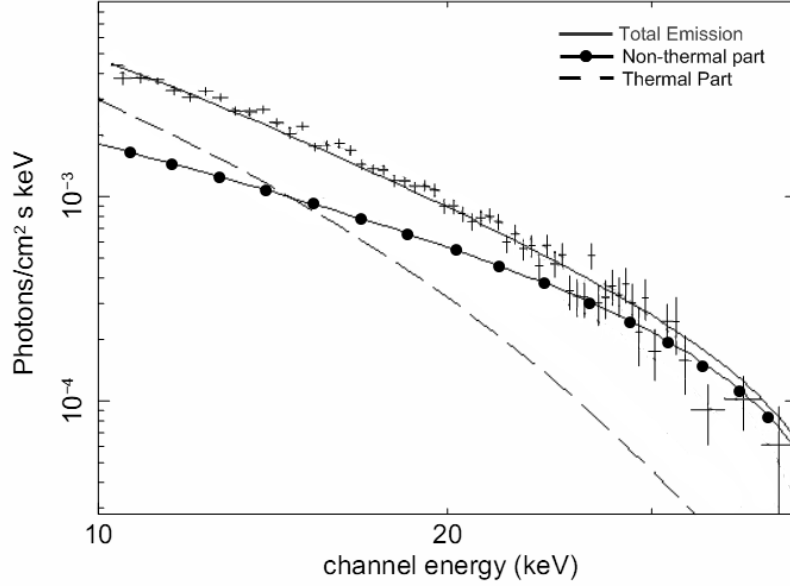
$$F_X^{\text{ib}}(E_X) = 4\pi \int_E dE \int_{V_{\text{GC}}} N_p(E, \mathbf{r}, t) \frac{d\sigma_{\text{br}}}{dE_X} v_p n(\mathbf{r}) d^3r, \quad (13)$$

where the  $V_{\text{GC}}$  is the volume of emitting region.

The calculated X-ray spectrum of inverse bremsstrahlung radiation is shown in figure 3 by the solid lines with points. The GC hard X-ray spectrum observed with the Suzaku HXD shown by crosses (Yuasa et al. 2008) was deconvolved to a photon-spectrum to perform a direct comparison with our model spectrum of inverse bremsstrahlung. In the deconvolution, as a rough approximation, we assumed a  $0.55^\circ \times 0.55^\circ$  spatially uniform emission (albeit in reality the surface brightness of the emission has spatial gradient centered on the GC). From spectral characteristics of the Suzaku flux it follows that the energy  $E_{\text{esc}}$  estimated by equation (1) is no smaller than 85 – 100 MeV, otherwise it is impossible to reproduce the Suzaku data. The total spectrum with the contribution of thermal emission is shown by the solid line. The total flux

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However we should use "field" curve instead that of around Sgr A\* because the HXD observes wider region, i.e.  $\sim \text{deg} \times \text{deg}$  scale around the Sgr A\*.



**Fig. 3.** The spectrum of inverse bremsstrahlung emission generated by subrelativistic protons ( $E_{\text{esc}} = 100 \text{ MeV}$  was assumed, see text) in the GC region (solid line with points) and the de-convolved X-ray flux observed by the Suzaku HXD in the GC region (crosses; Suzaku Observation ID 100027010). The thermal X-ray emission for the temperature 6.4 keV is shown by the dashed line and the total emission (thermal+inverse bremsstrahlung) is shown by the solid line. Normalization factors are adjusted so that the total model emission reproduces the observed HXD flux.

of thermal component (without absorption) in the energy range above 10 keV is  $F_X^{\text{th}} \simeq 2 \times 10^{36} \text{ erg s}^{-1}$ . The inverse bremsstrahlung flux for the same energy range is  $F_X^{\text{ib}} \simeq 3 \times 10^{36} \text{ erg s}^{-1}$ . We notice, however, that this estimate of the nonthermal emission from the hot plasma in the GC is an upper limit of the model, because continuum emission generated by these protons in the molecular gas may contribute a significant part of the total flux (see Dogiel et al. 2009b). Besides, if a part of line emission comes from individual sources, the effect of the non-thermal proton becomes smaller. Thus, the spectrum presented in figure 3 is the worst case for the model.

The calculated flux of inverse bremsstrahlung radiation from the  $0.55^\circ \times 0.55^\circ$  central region is weakly sensitive to the average density of background plasma in the GC if the spatial diffusion coefficient of protons is small enough. The reason is that (as it follows from Eqs. (5) and (13)) the total flux of inverse bremsstrahlung radiation can be estimated as

$$F_{\text{ib}} \sim \bar{Q} \frac{\tau_i}{\tau_{\text{ib}}}, \quad (14)$$

where  $\tau_i$  and  $\tau_{\text{ib}}$  are the characteristic times of ionization and bremsstrahlung losses of protons, and  $\bar{Q}$  is the integrated power of proton sources. Since both times are proportional to the plasma density, the inverse bremsstrahlung flux is almost independent of it.

We notice a significant discrepancy between the GC hard X-ray emission and that of the GRXE. The last one can hardly be due to inverse bremsstrahlung of subrelativistic nuclei since in this case the flux of carbon and oxygen de-excitation gamma-ray lines in the range from 3 to 7 MeV is higher than the upper limit measured by OSSE (Valinia et al. 2000). However, if the hard X-ray flux from the Galactic center is due to inverse bremsstrahlung of protons with the derived spectrum, the flux of de-excitation lines is still below the OSSE level (Dogiel et al. 2009a). In this respect common analysis of X-ray and gamma-ray data is crucial for the origin of hard X-rays from GC.

## 5. Conclusion

We analysed the origin of X-ray emission from GC assuming that it is produced by subrelativistic protons generated by star accretion on the central black hole. The average power of energy release from accretion is about  $10^{42}$  erg s $^{-1}$  and the average energy of emitted protons is about 100 MeV. The energy of high energy protons is transformed into plasma heating by ionization losses. As derived by Sunyaev et al. (1993); Koyama et al. (1996); Muno et al. (2004) just this energy release is necessary to heat the plasma up to temperatures about 6 – 10 keV, just as observed. Additional ionization of iron ions by nonrelativistic protons can, in principle, violate the ionization balance in GC providing an excess of FeXXVI ions that increases the intensity of 6.9 keV iron line. However, as numerical calculations show the excess due to ionization by subrelativistic protons is negligible for the 6.5 keV plasma temperature. A more significant effect from subrelativistic protons is expected in the X-ray range above 10 keV where influence of thermal emission is insignificant. We show that the inverse bremsstrahlung emission of protons in this energy range may produce a non-thermal X-ray flux. For the parameters of accretion the inverse bremsstrahlung flux of protons is about  $3 \times 10^{36}$  erg s $^{-1}$ , i.e. about the flux observed by the Suzaku from the GC in the 14 – 40 keV band.

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